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# A
# SHORT TREATISE
# ON THE
# COMPOUND STEAM ENGINE,
## WITH A
## NEW METHOD OF FINDING THE RELATIVE AREAS OF THE TWO CYLINDERS.

ILLUSTRATED WITH DIAGRAMS, TABLES, ETC.

BY

JOHN TURNBULL, Jr.

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# THE COMPOUND ENGINE.

The compound engine—whatever diversity of opinion may be held by engineers and others as to its merits as an economical expansive engine—has attracted towards itself a very considerable share of attention, from the superior results that have been obtained by it in many instances; and it is reasonable to suppose that, when a certain degree of perfection has once been attained in the manufacture of any machine, or economy secured by any new arrangement of its parts, similar machines can be so constructed as to give out the same results, if proper care is taken that the same arrangement and construction is faithfully carried out as in that of the more perfect machine. And when that degree of economy has not been obtained from a compound engine which had reasonably been expected, it would, no doubt, be found, if proper inquiry were made, that the fault lay, not in the principle that had been adopted, but that sufficient skill had not been exercised in properly proportioning the different parts through which the steam had to pass or come in contact on its way from the boiler to the condenser, and that sufficient means had not been employed to prevent or replace any waste of heat from condensation and other causes.

As the compound engine is being now so universally adopted in the Mercantile Marine Service, and a knowledge of its principles absolutely necessary by those engaged in attending it, we will, in the following remarks, explain these principles in as simple a manner as possible, and institute a comparison between the respective merits of the single-cylinder expansive condensing engine and the compound engine:

The compound engine is a high and low-pressure condensing engine, having two ordinary steam cylinders, the smaller or high-pressure cylinder communicating direct with the boiler, the larger or low-pressure condensing cylinder direct with the condenser, and both with each other. The steam is admitted freely from the boiler into the high-pressure cylinder until the piston has been moved through a certain distance where the valve is so regulated that the communication with the boiler is entirely shut off, and the remainder of the space to be passed through by the piston is performed by the expansion of the steam now shut up in the cylinder, and which, after doing its work in this cylinder, passes on to the condensing cylinder, where it does an equal or proportionate quantity of work, and then passes into the condenser.

It has been found from modern practice that when the length of stroke of both cylinders is the same, it is necessary that the condensing cylinder be about three times greater in area than the high-pressure one, and this proportion is best suited when the steam employed is from 45 to 50 lbs pressure above the atmosphere, and cutting off the steam after being admitted during $\frac{1}{3}$ of the stroke in the high-pressure cylinder. When the steam to be employed is of a less pressure, but the point of cut-off the same, then the relative proportions of the cylinders must be nearer to each other, and the reverse when steam of a greater pressure is to be used.

To get the maximum of economy out of any class of expansive condensing engine, the pressure of steam and point of cut-off must be so regulated that the steam passes into the condenser at the end of the stroke at a pressure not exceeding 5 lbs. above a perfect vacuum, and with steam at 45 lbs. pressure above the atmosphere, which is equal to 60 lbs. pressure above a perfect vacuum (the pressure of the atmosphere being considered as equal to 15 lbs. on the square inch), and a terminal pressure of 5 lbs., we get 12 expansions, because the pressure at the end of the stroke is 12 times less than what it was at the point off cut-off, and is expressed by the formula—

$$\frac{P}{t} = R.$$

Where $P =$ pressure at point of cut-off, $t =$ terminal pressure, and $R =$ ratio or number of expansions, and as the pressure of steam, according to Marriotte's law, varies inversely as the space it occupies, the steam will now fill 12 times the space it originally occupied at a pressure equal to $\frac{1}{12}$th of the original pressure, that is, supposing there had been no loss of heat during the process of expansion, and this we must suppose to simplify this inquiry.

On reference to the annexed table of average pressures, it will be seen that steam admitted at 60 lbs. pressure, and cut-off at $\frac{1}{12}$th part of the stroke, exerts an average pressure = 17.32 lbs. per sq. in. on the piston throughout the whole stroke, and, although this is 3½ times less work than would have been done had the steam been used at the full pressure of 60 lbs. throughout the whole length of the stroke, still only a 12th part of the cylinder's contents had been filled from the boiler, and the power required is thus got by working the steam expansively, at a saving equal to about 3½ to 1. (See Table A.)

## TABLE A.—AVERAGE PRESSURE

### FOR ANY RATE

| Steam cut off at | Pressure in Lbs. at Com- | | | | | | |
|---|---|---|---|---|---|---|---|
| | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 1/3 | 21 | 24½ | 28 | 31½ | 35 | 38½ | 42 |
| 2/3 | 28¼ | 32¾ | 37½ | 42 | 46¾ | 51½ | 56¼ |
| 1/4 | 17¾ | 20¾ | 23¾ | 26¾ | 29¾ | 32¾ | 35¾ |
| 1/2 | 25¼ | 29½ | 33¾ | 38 | 42¼ | 46½ | 50¾ |
| 3/4 | 28¾ | 33½ | 38½ | 43¼ | 48¼ | 53 | 57¾ |
| 1/5 | 15½ | 18¼ | 20¾ | 23½ | 26 | 28½ | 31¼ |
| 2/5 | 23 | 26¾ | 30½ | 34½ | 38¼ | 42 | 46 |
| 3/5 | 27 | 31½ | 36¼ | 40¾ | 45¼ | 49¾ | 54¼ |
| 4/5 | 29¼ | 34¼ | 39 | 44 | 49 | 53¾ | 58½ |
| 1/6 | 14 | 16¼ | 18½ | 20¾ | 23¼ | 25½ | 27¾ |
| 5/6 | 29½ | 34½ | 39½ | 44¼ | 49¼ | 54 | 59 |
| 1/7 | 12½ | 14¾ | 16¾ | 18¾ | 21 | 23¼ | 25¼ |
| 2/7 | 19¼ | 22½ | 25¾ | 28¾ | 32 | 35¼ | 38½ |
| 3/7 | 23¾ | 27¾ | 31½ | 35½ | 39½ | 43½ | 47½ |
| 4/7 | 26¾ | 31¼ | 35½ | 40 | 44½ | 49 | 53½ |
| 5/7 | 28½ | 33½ | 38¼ | 42¾ | 47¾ | 52½ | 57¼ |
| 6/7 | 29½ | 34½ | 39½ | 44½ | 49½ | 54¼ | 59¼ |
| 1/8 | 11½ | 13½ | 15¼ | 17¼ | 19¼ | 21¼ | 23 |
| 3/8 | 22¼ | 26 | 29¾ | 33½ | 37 | 40¾ | 44½ |
| 5/8 | 27½ | 32 | 36¾ | 41¼ | 45½ | 50½ | 55¼ |
| 7/8 | 29¾ | 34¾ | 39½ | 44½ | 49½ | 54½ | 59½ |
| 1/9 | 10½ | 12¼ | 14¼ | 15¾ | 17¾ | 19½ | 21¼ |
| 2/9 | 16½ | 19¼ | 22¼ | 25 | 27¾ | 30½ | 33¼ |
| 4/9 | 24 | 28 | 32 | 36 | 40¼ | 44¼ | 48¼ |
| 5/9 | 26¼ | 30¾ | 35¼ | 39½ | 44 | 48½ | 52¾ |
| 7/9 | 29 | 34 | 38¾ | 43¾ | 48½ | 53½ | 58¼ |
| 8/9 | 29¾ | 34¾ | 39¾ | 44½ | 49½ | 54½ | 59½ |
| 1/11 | 9¼ | 10¾ | 12¼ | 13¾ | 15¼ | 16¾ | 18½ |
| 2/11 | 14¾ | 17¼ | 19½ | 22 | 24½ | 27 | 29½ |
| 3/11 | 18¾ | 21¾ | 25 | 28 | 31¼ | 34¼ | 37½ |
| 4/11 | 21¾ | 25½ | 29¼ | 32¾ | 36½ | 40¼ | 43¾ |
| 5/11 | 24¼ | 28¼ | 32½ | 36½ | 40½ | 44½ | 48¾ |
| 6/11 | 26¼ | 30½ | 35 | 39¼ | 43¾ | 48 | 52½ |
| 7/11 | 27½ | 32¼ | 36¾ | 41½ | 46 | 50¾ | 55¼ |
| 8/11 | 28¾ | 33½ | 38¼ | 43 | 47¾ | 52¾ | 57½ |
| 9/11 | 29¼ | 34¼ | 39¼ | 44 | 49 | 54 | 58¾ |
| 1/12 | 8½ | 10 | 11½ | 13 | 14½ | 15¾ | 17¼ |

## UPON PISTON DURING ONE STROKE.

OF EXPANSION.

mencement of Stroke.

| 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 |
|---|---|---|---|---|---|---|---|
| 45½ | 49 | 52½ | 56 | 59½ | 63 | 66½ | 70 |
| 61 | 65½ | 70¼ | 75 | 79½ | 84½ | 89 | 93¾ |
| 38¾ | 41¾ | 44¾ | 47¾ | 50¾ | 53¾ | 56¾ | 59¾ |
| 55 | 59¼ | 63½ | 67¾ | 72 | 76¼ | 80½ | 84¾ |
| 62½ | 67½ | 72¼ | 77¼ | 82 | 87 | 91¾ | 96½ |
| 34 | 36½ | 39 | 41¾ | 44¼ | 47 | 49½ | 52¼ |
| 49¾ | 53½ | 57½ | 61¼ | 65 | 69 | 72¾ | 76½ |
| 58¾ | 63¼ | 67¾ | 72½ | 77 | 81½ | 86 | 90½ |
| 63½ | 68½ | 73¾ | 78¼ | 83 | 88 | 92¾ | 97¾ |
| 30¼ | 32½ | 34¾ | 37¼ | 39½ | 41¾ | 44¼ | 46½ |
| 64 | 69 | 73¾ | 78¾ | 83¾ | 88¾ | 93½ | 98½ |
| 27¼ | 29½ | 31½ | 33½ | 35¾ | 37¾ | 40 | 42 |
| 41¾ | 45 | 48¼ | 51½ | 54½ | 57¾ | 61 | 64¼ |
| 51½ | 55¼ | 59¼ | 63¼ | 67¼ | 71¼ | 75¼ | 79 |
| 57¾ | 62½ | 66¾ | 71¼ | 75¾ | 80 | 84½ | 89 |
| 62 | 66¾ | 71½ | 76¼ | 81 | 85¾ | 90¾ | 95½ |
| 63¾ | 69¼ | 74¼ | 79 | 84 | 89 | 93¾ | 98¾ |
| 25 | 27 | 28¾ | 30¾ | 32¾ | 34½ | 36½ | 38½ |
| 48¼ | 52 | 55¾ | 59½ | 63 | 66¾ | 70½ | 74¼ |
| 59¾ | 64¼ | 68¾ | 73½ | 78 | 82½ | 87¼ | 91¾ |
| 64½ | 69¼ | 74¼ | 79¼ | 84¼ | 89¼ | 94¼ | 99 |
| 23 | 24¾ | 26½ | 28¼ | 30¼ | 31¾ | 33¾ | 35½ |
| 36 | 38¾ | 41¾ | 44½ | 47¼ | 50 | 52¾ | 55½ |
| 52¼ | 56¼ | 60¼ | 64¼ | 68¼ | 72¼ | 76¼ | 80½ |
| 56½ | 61¾ | 66 | 70½ | 74¾ | 79¼ | 83¾ | 88 |
| 63¼ | 68 | 72¾ | 77¾ | 82¾ | 87½ | 92¼ | 97¼ |
| 64½ | 69½ | 74½ | 79¼ | 84¼ | 89¼ | 94¼ | 99¼ |
| 20 | 21½ | 23 | 24½ | 26¼ | 27¾ | 29¼ | 30¾ |
| 31¾ | 34¼ | 36¾ | 39¼ | 41¾ | 44¼ | 46¾ | 49 |
| 40¾ | 43¾ | 47 | 50 | 53¼ | 56¼ | 59½ | 62½ |
| 47½ | 51 | 54¾ | 58½ | 62 | 65¾ | 69½ | 73 |
| 52¾ | 56¾ | 60¾ | 65 | 69 | 73 | 77 | 81¼ |
| 56¾ | 61¼ | 65½ | 70 | 74¼ | 78¾ | 83 | 87½ |
| 60 | 64½ | 69¼ | 73¾ | 78½ | 83 | 87¾ | 92¼ |
| 62¼ | 67 | 71¾ | 76¾ | 81½ | 86¼ | 91 | 95¾ |
| 63¾ | 68¾ | 73½ | 78½ | 83½ | 88¼ | 93¼ | 98¼ |
| 18¾ | 20¼ | 21¾ | 23¼ | 24½ | 26 | 27½ | 29 |

Average Pressure in Lbs. upon the Piston.

TABLE A.—Continued.

| Steam cut off at | Pressure in Lbs. at Commencement of Stroke— | | | | |
|---|---|---|---|---|---|
| | 110 | 120 | 130 | 140 | 150 |
| 1/3 | 77½ | 84 | 91 | 98 | 105 |
| 2/3 | 103 | 111½ | 121¾ | 131 | 140½ |
| 1/4 | 65½ | 71½ | 77½ | 83½ | 89½ |
| 1/2 | 93¼ | 101½ | 110 | 118½ | 127 |
| 3/4 | 106¼ | 115¾ | 125½ | 135¼ | 144¾ |
| 1/5 | 57¼ | 62½ | 67¾ | 73 | 78½ |
| 2/5 | 84¼ | 91¾ | 99½ | 107¼ | 115 |
| 3/5 | 99½ | 108¾ | 117¾ | 126¾ | 135 |
| 4/5 | 107½ | 117½ | 127¼ | 136¾ | 146¾ |
| 1/6 | 51¼ | 55¾ | 60½ | 65 | 69¾ |
| 5/6 | 108¼ | 118¼ | 128 | 137¾ | 147 |
| 1/7 | 46¼ | 50½ | 54¾ | 58¾ | 63 |
| 2/7 | 70¾ | 77¼ | 83½ | 90 | 96½ |
| 3/7 | 87 | 94¼ | 102¼ | 110¾ | 118¾ |
| 4/7 | 98 | 106¾ | 115¾ | 124¾ | 133½ |
| 5/7 | 105 | 114¼ | 124 | 133½ | 143¼ |
| 6/7 | 108¾ | 118¾ | 128½ | 138½ | 148¼ |
| 1/8 | 42¾ | 46¼ | 50 | 54½ | 57¾ |
| 3/8 | 81¾ | 89 | 96½ | 104 | 111½ |
| 5/8 | 101 | 110¼ | 119½ | 128½ | 137¾ |
| 7/8 | 109 | 119 | 128¾ | 138¾ | 148¾ |
| 1/9 | 39 | 42½ | 46 | 49½ | 53¼ |
| 2/9 | 61 | 66¾ | 72¼ | 77¾ | 83 |
| 4/9 | 88½ | 96½ | 104½ | 112½ | 120½ |
| 5/9 | 97 | 105¾ | 114½ | 123¼ | 132¼ |
| 7/9 | 107 | 116¾ | 126½ | 136¼ | 145 |
| 8/9 | 109¼ | 119¼ | 129 | 139 | 149 |
| 1/11 | 33¾ | 37 | 40 | 43¼ | 46¼ |
| 2/11 | 54 | 59 | 63¾ | 68¾ | 73¾ |
| 3/11 | 68¾ | 75¼ | 81½ | 87¾ | 94 |
| 4/11 | 80¼ | 87¾ | 95 | 102¼ | 109½ |
| 5/11 | 89¼ | 97½ | 105½ | 113¾ | 121¾ |
| 6/11 | 96¼ | 105 | 113¾ | 122½ | 131 |
| 7/11 | 101½ | 110¾ | 120 | 129¼ | 138½ |
| 8/11 | 105¼ | 115 | 124½ | 134¼ | 143½ |
| 9/11 | 108 | 117¾ | 127½ | 137½ | 147¼ |
| 1/12 | 31¾ | 34¾ | 37¾ | 40½ | 43½ |

Average Pressure in Lbs. upon the Piston.

As the point of cut-off may be different from any of those shown in the table, it is as well that the student should be in possession of a simple formula for ascertaining the average pressure for himself at any time, and the following is given to find out the mean pressure during a stroke in lbs. per sq. in. Let—

$L$ = Whole length of stroke in inches.
$l$ = Distance travelled by piston before the steam is cut off, in inches.
$R$ = Ratio or number of expansions = $\frac{L}{l}$.
$H$ = Hyperbolic logarithm of $R$.
$P$ = Initial pressure of steam in lbs. per sq. in.
$p$ = Mean pressure during the stroke in lbs. per square inch.

Then, $p = P\,\frac{1 + H}{R}.$

A table of hyperbolic logarithms is also annexed so that $H$ may be found without any difficulty.

## TABLE OF HYPERBOLIC LOGARITHMS.

The Hyperbolic Logarithm of a number is found by multiplying the common Logarithm of the number by 2.30259.

| No. | Logarithm. |
|---|---|
| 1–1 | .0953102 |
| 1–2 | .1823215 |
| 1–3 | .2623642 |
| 1–4 | .3364722 |

| No. | Logarithm. |
|---|---|
| 1-5 | .4054652 |
| 1-6 | .4700036 |
| 1-7 | .5306282 |
| 1-8 | .5877866 |
| 1-9 | .6418538 |
| 2-0 | .6931472 |
| 2-1 | .7419373 |
| 2-2 | .7884573 |
| 2-3 | .8329090 |
| 2-4 | .8754686 |
| 2-5 | .9162907 |
| 2-6 | .9555113 |
| 2-7 | .9932518 |
| 2-8 | 1.0296913 |
| 2-9 | 1.0647107 |
| 3-0 | 1.0986124 |
| 3-1 | 1.1314021 |
| 3-2 | 1.1631508 |
| 3-3 | 1.1939224 |
| 3-4 | 1.2237754 |
| 3-5 | 1.2527629 |
| 3-6 | 1.2809338 |
| 3-7 | 1.3083328 |
| 3-8 | 1.3350010 |
| 3-9 | 1.3609765 |
| 4-0 | 1.3862943 |
| 4-1 | 1.4109869 |
| 4-2 | 1.4350845 |
| 4-3 | 1.4586149 |
| 4-4 | 1.4816045 |
| 4-5 | 1.5040773 |
| 4-6 | 1.5260563 |
| 4-7 | 1.5475625 |
| 4-8 | 1.5686159 |
| 4-9 | 1.5892352 |
| 5-0 | 1.6094379 |
| 5-1 | 1.6292405 |
| 5-2 | 1.6486586 |
| 5-3 | 1.6677068 |
| 5-4 | 1.6863989 |
| 5-5 | 1.7047481 |
| 5-6 | 1.7227665 |
| 5-7 | 1.7404661 |

| No. | Logarithm. |
|---|---|
| 5–8 | 1.7578579 |
| 5–9 | 1.7749523 |
| 6–0 | 1.7917595 |
| 6–1 | 1.8082887 |
| 6–2 | 1.8245493 |
| 6–3 | 1.8405496 |
| 6–4 | 1.8562979 |
| 6–5 | 1.8718021 |
| 6–6 | 1.8870697 |
| 6–7 | 1.9021075 |
| 6–8 | 1.9169226 |
| 6–9 | 1.9315214 |
| 7–0 | 1.9459100 |
| 7–1 | 1.9600947 |
| 7–2 | 1.9740810 |
| 7–3 | 1.9878743 |
| 7–4 | 2.0014800 |
| 7–5 | 2.0149030 |
| 7–6 | 2.0281482 |
| 7–7 | 2.0412203 |
| 7–8 | 2.0541237 |
| 7–9 | 2.0668627 |
| 8–0 | 2.0794414 |
| 8–1 | 2.0918640 |
| 8–2 | 2.1041341 |
| 8–3 | 2.1162555 |
| 8–4 | 2.1282317 |
| 8–5 | 2.1400661 |
| 8–6 | 2.1517622 |
| 8–7 | 2.1633230 |
| 8–8 | 2.1747517 |
| 8–9 | 2.1860512 |
| 9–0 | 2.1972245 |
| 9–1 | 2.2082744 |
| 9–2 | 2.2192034 |
| 9–3 | 2.2300144 |
| 9–4 | 2.2407096 |
| 9–5 | 2.2512907 |
| 9–6 | 2.2617631 |
| 9–7 | 2.2721258 |
| 9–8 | 2.2823823 |
| 9–9 | 2.2925347 |
| 10–0 | 2.3025851 |

| No. | Logarithm. |
|---|---|
| 11–0 | 2.3978953 |
| 12–0 | 2.4849065 |
| 13–0 | 2.5649494 |
| 14–0 | 2.6390572 |
| 15–0 | 2.7080502 |
| 16–0 | 2.7726067 |
| 17–0 | 2.8332341 |
| 18–0 | 2.8903847 |
| 19–0 | 2.9444497 |
| 20–0 | 2.9957322 |
| 21–0 | 3.0445437 |
| 22–0 | 3.0910562 |
| 23–0 | 3.1354964 |
| 24–0 | 3.1780715 |
| 25–0 | 3.2188757 |
| 26-0 | 3.2581099 |
| 27–0 | 3.2958495 |
| 28-0 | 3.3322306 |
| 29–0 | 3.3672992 |
| 30-0 | 3.4011974 |

In order to arrive at the merits and capabilities of the compound engine, let us first see what are the results got from a single-cylinder condensing engine of given dimensions and cutting off the steam to work with a certain number of expansions. Let—

$D$ = Diameter of cylinder in inches,
$L$ = Length of stroke in feet,
$N$ = Number of revolutions of crank per minute,
$p$ = Mean or average pressure on piston,

then, for arriving at the horse power we use the following formula :—

$$\frac{D^2 \times .7854 \times 2\,L \times N \times p}{33.000} = \text{horse-power.}$$

But as $D^2 \times .7854$ = area of piston, and $2\,L \times N$ = speed of piston in feet per minute, we will make $D^2 \times .7854 = A$, and $2\,L \times N = S$, the formula then becomes

$$\frac{A \times S \times p}{33.000} = \text{H. P.}$$

and supposing the cylinder to be 24 in. diameter, length of stroke=4 ft.; number of revolutions per minute=50 ; pressure of steam at beginning of stroke=60 lbs. (all pressures here mentioned are above a perfect vacuum), point of cut-off, $= \frac{1}{12}$th part of the stroke, or, after the piston has travelled 4 in., so that—

$D$ = 24 inches.
$2\,L$ = 8 feet.
$N$ = 50 revolutions.
$P$ = 60 lbs.
$p = P\,\frac{1 \times H}{R} = 17.32$, we get—

$$\frac{452\ 4 \times 400 \times 17\ 32}{33.000} = 95 \text{ horse-power;}$$

To distribute this power equally over the working parts of a compound engine, it is desirable that both cylinders be so proportioned that they will each give out nearly the same power, and that the thrust caused by the entrance of the steam at the beginning of each stroke be the same in both cylinders.

To attain this with an accuracy sufficient for all practical purposes, it is necessary that the condensing cylinder be larger than the high-pressure cylinder in area, by the ratio of expansion that takes place in the high-pressure cylinder; that is to say, if

$a$ = area of piston in high-pressure cylinder,
$r$ = ratio of expansion in high-pressure cylinder,
A = area of piston in condensing cylinder, then

$$A = a\,r.$$

So that if $P$ = initial pressure in small cylinder, and $P'$ = initial pressure in large cylinder, the area of large piston, multiplied by $P'$, will be equal to the area of small piston multiplied by $P$, then $P'\,A = P\,a$.

But as the ratio of expansion is the same in both cylinders, and the whole ratio of expansion equal to the initial pressure in small cylinder, divided by the terminal pressure in large cylinder, we get $\sqrt{\frac{P}{t}}=$ ratio of expansion in each cylinder, and as we have already taken $P=60$ lbs., and $t=$ 5 lbs., we have $\sqrt{\frac{60}{5}}=3.46=$ differences of area of the two pistons, and also ratio oı expansion in each cylinder, and consequently$=r$.

From the nature of the compound engine, the area opened up for the steam by the movement of the large piston is at all times decreased by a proportionate part $=\frac{A}{a\ r}$ $=1$, by the advancing area of small piston, so that the space actually occupied by the expanding steam is $=A-1$, and from this we get the formula for ascertaining the average pressure in the condensing cylinder of a compound engine.

$$p'=P'\frac{H}{R-1.}$$

A table showing the relative areas of the two cylinders of a compound engine, with the average pressure in each cylinder, etc.:

| P | R | P′ | H | S | p′ | p |
|---|---|---|---|---|---|---|
| 30 | 2.449 | 12.25 | .896 | 23.23 | 7.52 | 15.71 |
| 35 | 2.645 | 13.22 | .972 | 26.10 | 7.83 | 18.27 |
| 40 | 2.828 | 14.14 | 1.040 | 28.85 | 8.04 | 20.81 |
| 45 | 3.000 | 15.00 | 1.098 | 31.47 | 8.22 | 23.25 |
| 50 | 3.162 | 15.86 | 1.150 | 34.00 | 8.40 | 25.60 |
| 55 | 3.316 | 16.58 | 1.197 | 36.44 | 8.58 | 27.86 |
| 60 | 3.464 | 17.32 | 1.242 | 38.83 | 8.74 | 30.09 |
| 65 | 3.605 | 18.02 | 1.281 | 41.13 | 8.85 | 32.28 |
| 70 | 3.741 | 18.70 | 1.319 | 43.39 | 9.08 | 34.31 |
| 75 | 3.872 | 19.36 | 1.353 | 45.57 | 9.11 | 36.46 |
| 80 | 4.000 | 20.00 | 1.386 | 47.72 | 9.24 | 38.48 |
| 85 | 4.123 | 20.61 | 1.415 | 49.78 | 9.34 | 40.44 |
| 90 | 4.242 | 21.21 | 1.444 | 51.85 | 9.44 | 42.41 |
| 95 | 4.358 | 21.80 | 1.470 | 53.84 | 9.56 | 44.28 |
| 100 | 4.472 | 22.36 | 1.497 | 55.84 | 9.64 | 46.20 |
| 105 | 4.582 | 22.91 | 1.521 | 57.77 | 9.73 | 48.04 |
| 110 | 4.690 | 23.45 | 1.545 | 59.69 | 9.82 | 49.87 |
| 115 | 4.795 | 23.98 | 1.567 | 61.57 | 9.89 | 51.68 |
| 120 | 4.898 | 24.45 | 1.589 | 63.43 | 9.96 | 53.47 |
| 125 | 5.000 | 25.00 | 1.609 | 65.32 | 10.05 | 55.27 |
| 130 | 5.099 | 25.50 | 1.629 | 67.02 | 10.13 | 56.89 |
| 135 | 5.196 | 26.00 | 1.647 | 68.77 | 10.21 | 58.66 |
| 140 | 5.291 | 26.46 | 1.665 | 70.51 | 10.26 | 60.25 |
| 145 | 5.385 | 26.93 | 1.683 | 72.25 | 10.32 | 61.93 |
| 150 | 5.477 | 27.38 | 1.700 | 73.95 | 10.38 | 63.57 |
| 155 | 5.567 | 27.84 | 1.716 | 75.67 | 10.46 | 65.21 |
| 160 | 5.656 | 28.32 | 1.732 | 77.28 | 10.52 | 66.76 |
| 165 | 5.744 | 28.72 | 1.748 | 78.93 | 10.58 | 68.35 |
| 170 | 5.830 | 29.15 | 1.763 | 80.56 | 10.64 | 69.92 |
| 175 | 5.916 | 29.58 | 1.777 | 82.14 | 10.70 | 71.44 |
| 180 | 6.000 | 30.00 | 1.791 | 83.73 | 10.75 | 72.98 |
| 185 | 6.082 | 30.41 | 1.805 | 85.32 | 10.80 | 74.52 |
| 190 | 6.164 | 30.82 | 1.818 | 86.86 | 10.85 | 76.91 |

The accompanying table has been drawn out for easy reference in conformity with this rule. The first column $= P =$ the initial pressure of the steam above a perfect vacuum on entering the small cylinder; the second $= R = \sqrt{\frac{P}{t}}$ shows the relative areas of the two cylinders, and also the number of expansions in high-pressure cylinder; the third column, $= P =$ the terminal pressure in high-pressure cylinder, gives the pressure at beginning of stroke in condensing cylinder; the fourth column, $= H$, contains the hyperbolic logarithms of R; the fifth, $= S$, gives the average pressure during a stroke in a single cylinder, for the different values of R and $= P\,\frac{1+H}{R}$; the sixth column, $= p'$, gives the average pressure during a stroke in the condensing cylinder of a compound engine, and $= P'\frac{H}{R-1}$ and the last column, p, gives the average pressure during a stroke in the high-pressure cylinder $P = \frac{1+H}{R} - P'\,\frac{H}{R-1}$.

Now, as the power to be given out by both cylinders is to be the same, the power that is required to be given out by A = $\frac{95}{2}$ = 47.5 horse-power, and as $\sqrt{\frac{60}{5}}$ = 3.464, $t \times 3.464 = 17.32 = P'$, and from the above formula we get $p' = 17.32 \frac{H}{R-1} =$ 8.74 lbs. average pressure per square inch on piston. So that we can now get what area of piston is required to give out this power by

$$\frac{47.5 \times 33.000}{400 \times 8.74} = 450 = 24'' \text{ diameter.}$$

and as the area of the two pistons are to each other as 1 to 3.464, we get the area of small piston = 130 sq. in. = 13″ diameter.

## Table of the pressure, temperature, volume, and mechanical effect of steam.

| Total pressure in lbs. per square inch. | Corresponding temperature. | Volume of steam compared with volume of water. | Mechanical effect of a cubic inch of water evaporated, in lbs. raised 1 ft. high. |
|---|---|---|---|
| 1 | 102 9 | 20868 | 1739 |
| 2 | 126.1 | 10874 | 1812 |
| 3 | 141.0 | 7437 | 1859 |
| 4 | 152.3 | 5685 | 1895 |
| 5 | 161.4 | 4617 | 1924 |
| 6 | 169.2 | 3897 | 1948 |
| 7 | 175.9 | 3376 | 1969 |
| 8 | 182.0 | 2983 | 1989 |
| 9 | 187.4 | 2674 | 2006 |
| 10 | 192.4 | 2426 | 2022 |
| 11 | 197.0 | 2221 | 2036 |
| 12 | 201.3 | 2050 | 2050 |
| 13 | 205.3 | 1904 | 2063 |
| 14 | 209.1 | 1778 | 2074 |
| 15 | 212.8 | 1669 | 2086 |
| 16 | 216.3 | 1573 | 2097 |
| 17 | 219.6 | 1488 | 2107 |
| 18 | 222.7 | 1411 | 2117 |
| 19 | 225.6 | 1343 | 2126 |
| 20 | 228.5 | 1281 | 2135 |
| 21 | 231 2 | 1225 | 2144 |
| 22 | 233.8 | 1174 | 2152 |
| 23 | 236.3 | 1127 | 2160 |
| 24 | 238.7 | 1084 | 2168 |
| 25 | 241.0 | 1044 | 2175 |
| 26 | 243.3 | 1007 | 2182 |
| 27 | 245.5 | 973 | 2189 |
| 28 | 247.6 | 941 | 2196 |
| 29 | 249 6 | 911 | 2202 |
| 30 | 251.6 | 883 | 2209 |

| Total pressure in lbs. per square inch. | Corresponding temperature. | Volume of steam compared with volume of water. | Mechanical effect of a cubic inch of water evaporated, in lbs. raised 1 ft. high. |
|---|---|---|---|
| 31...... | 253.6 | 857 | 2215 |
| 32...... | 255.5 | 833 | 2221 |
| 33...... | 257.3 | 810 | 2226 |
| 34...... | 259.1 | 788 | 2232 |
| 35...... | 260.9 | 767 | 2238 |
| 36...... | 262.6 | 748 | 2243 |
| 37...... | 264.3 | 729 | 2248 |
| 38...... | 365.9 | 712 | 2253 |
| 39...... | 367.5 | 695 | 2259 |
| 40...... | 269.1 | 679 | 2264 |
| 41...... | 270.6 | 664 | 2268 |
| 42...... | 272.1 | 649 | 2273 |
| 43...... | 273.6 | 635 | 2278 |
| 44...... | 275.0 | 622 | 2282 |
| 45...... | 276.4 | 610 | 2287 |
| 46..... | 277.8 | 598 | 2291 |
| 47...... | 279.2 | 586 | 2296 |
| 48...... | 280.5 | 575 | 2300 |
| 49...... | 281.9 | 564 | 2304 |
| 50...... | 283.2 | 554 | 2308 |
| 51...... | 284.4 | 544 | 2312 |
| 52...... | 285.7 | 534 | 2316 |
| 53...... | 286.9 | 525 | 2320 |
| 54 ..... | 288.1 | 516 | 2324 |
| 55...... | 289.3 | 508 | 2327 |
| 56...... | 290.5 | 500 | 2331 |
| 57...... | 291.7 | 492 | 2335 |
| 58..... | 292.9 | 484 | 2339 |
| 59...... | 294.2 | 477 | 2343 |
| 60...... | 295.6 | 470 | 2347 |
| 61...... | 296.9 | 463 | 2351 |
| 62...... | 298.1 | 456 | 2355 |
| 63...... | 299.2 | 449 | 2359 |

| Total pressure in lbs. per square inch. | Corresponding temperature. | Volume of steam compared with volume of water. | Mechanical effect of a cubic inch of water evaporated, in lbs. raised 1 ft. high. |
|---|---|---|---|
| 64...... | 300.3 | 443 | 2362 |
| 65...... | 301.3 | 437 | 2365 |
| 66...... | 302.4 | 431 | 2369 |
| 67...... | 303.4 | 425 | 2372 |
| 68...... | 304.4 | 419 | 2675 |
| 69...... | 305.4 | 414 | 2378 |
| 70...... | 306.4 | 408 | 2382 |
| 71...... | 307.4 | 403 | 2385 |
| 72...... | 308.4 | 398 | 2388 |
| 73...... | 309 3 | 393 | 2391 |
| 74...... | 310.3 | 388 | 2394 |
| 75...... | 311.2 | 383 | 2397 |
| 76...... | 312.2 | 379 | 2400 |
| 77...... | 313.1 | 374 | 2403 |
| 78...... | 314.0 | 370 | 2405 |
| 79...... | 314.9 | 366 | 2408 |
| 80...... | 315.8 | 362 | 2411 |
| 81...... | 316.7 | 358 | 2414 |
| 82...... | 317.6 | 354 | 2417 |
| 83...... | 318.4 | 350 | 2419 |
| 84..... | 319.3 | 346 | 2422 |
| 85...... | 320.1 | 342 | 2425 |
| 86...... | 321.0 | 339 | 2427 |
| 87...... | 321.8 | 335 | 2430 |
| 88...... | 322.6 | 332 | 2432 |
| 89...... | 323.5 | 328 | 2435 |
| 90...... | 324.3 | 325 | 2438 |
| 91 ...... | 325.1 | 322 | 2440 |
| 92...... | 325.9 | 319 | 2443 |
| 93...... | 326.7 | 316 | 2445 |
| 94...... | 327.5 | 313 | 2448 |
| 95...... | 328.2 | 310 | 2450 |
| 96...... | 329.0 | 304 | 2453 |

| Total pressure in lbs. per square inch. | Corresponding temperature. | Volume of steam compared with volume of water. | Mechanical effect of a cubic inch of water evaporated, in lbs. raised 1 ft. high. |
|---|---|---|---|
| 97 | 329.8 | 304 | 2455 |
| 98 | 330.5 | 301 | 2457 |
| 99 | 331.3 | 298 | 2460 |
| 100 | 332.0 | 295 | 2462 |
| 110 | 339.2 | 271 | 2486 |
| 120 | 345.8 | 251 | 2507 |
| 130 | 352.1 | 233 | 2527 |
| 140 | 357.9 | 218 | 2545 |
| 150 | 363.4 | 205 | 2561 |
| 160 | 368.7 | 193 | 2577 |
| 170 | 373.6 | 183 | 2593 |
| 180 | 378.4 | 174 | 2608 |

From this we can see that for a compound engine to exert the same power as a single-cylinder condensing engine with the same number of expansions in both cases, the condensing cylinder of the compound engine requires to be equal in diameter to the single condensing cylinder; and from this being the case, it is quite reasonable to say, that if the power exerted can be got from one cylinder with the steam expanded a certain number of times, it would be unwise to add to the expense of the engine by expanding the same number of times in two cylinders instead of one. But as the source of the power obtained is the heat passed into the cylinder from the boiler, and as the economical working of the engine depends on the greatest quantity of this heat that can be converted into power, it is herein where the compound engine has the advantage over any other class of engine, and we will compare the single and the compound engine from this point of view.

The steam enters the single-cylinder engine at a pressure=60 lbs. per sq. in., the temperature of which, on reference to the annexed table, will be found to be equal to 295.6 deg. After doing its work it terminates with a pressure = 5 lbs.=161.4 deg. in temperature, and consequently has cooled down the cylinder to the same temperature, so that the fresh steam on entering to perform the next stroke can only be effective at a temperature corresponding to its pressure, and it has to part with its heat until it brings the cylinder up to its own temperature, and has consequently to be supplied with new steam from the boiler to do its work.

Now the pressure at the beginning of the stroke of the high pressure cylinder of the compound engine is the same=60 lbs. per sq. in.; but owing to the fewer number of expansions carried out in this one cylinder, it terminates this stroke with a pressure=17.32 lbs. per sq. in., the temperature of which will be found on reference to be 220 deg., being a difference of only 76 deg. instead of 135 deg., or just about one-half. A great part of this waste of the heat that is passed into the cylinder can be prevented by having a space round about the cylinder, and at both ends, filled with steam at the boiler pressure; but this steam jacket, as it is called, is much more effective in the compound engine than in the single cylinder engine, for this reason: It has been found from experiment that the rapidity with which two volumes of steam of different temperatures seek to equalize themselves is as the square of their difference in temperature, that is to say—that if you mix steam of 200 deg. with steam of 100 deg., and steam of 400 deg. with steam of 100 deg., the difference of temperatures of the former being as 2 to 1, and of the latter as 4 to 1, and as $2^2=4$, and $4^2=16$; the latter temperatures will seek to equalize themselves four times quicker than the former, and, as the variation of temperature is much greater in the single cylinder than in either of the cylinders of a compound engine, the heat from the steam jacket must pass through the metal with great rapidity to replace that wasted by condensation, and this it cannot do so effectively as when the temperatures are not so widely varied; and this is one of the great advantages possessed by the compound or double-cylinder engine. Another feature in which the compound engine bears favorable comparison with the single-cylinder engine is in the difference of the thrust caused by the entrance of the steam at the beginning of each stroke, and consequently on the amount of pressure or friction thrown on the crank pin and crank shaft journals, compared with the power to be exerted. If we multiply the area of piston in single cylinder by the initial pressure, we get 452×60=27,120 lbs. total pressure, or equal to a blow of fully 12 tons at the beginning of the stroke. If, in like manner, we multiply the areas of both pistons of the compound engine by their respective initial pressures we get 131×60=7,860 and 452×17.32=7,828, which being added together, gives a total pressure at beginning of stroke when both pistons are moving simultaneously=15,688 lbs.=about 7 tons or little more than one-half of that in the single cylinder, and from this it can be easily seen that as a less shock is given to the working parts by about one-half, the dimensions of these parts can be made proportionately less, and a gentler, steaddier, but equally effective motion is imparted.

The compound engine, both for marine and stationary purposes, has had the position of its cylinders and the combinations of its parts arranged in many different ways, in some cases to suit the space available for its erection, and in others, according to the different ideas of the different manufacturers; but the principle being the same in all cases, an equal economy should be got if care is taken in so proportioning the passages for the steam that no undue obstruction is caused, and that proper and efficient means are employed to prevent any waste of heat as far as possible.

The principle of the compound engine was known as early as 1781, when a patent was taken out by Jonathan Hornblower for "Employing the steam after it has acted on the first vessel to operate a second time in the other by permitting it to expand itself." But Hornblower was never able to carry out the principle to be of much practical use, owing to Watt's patents being in existence at the time.

The earliest compound engine in which the principle was practically carried out was patented in 1804 by Arthur Woolf, and his style of engine has been in use almost ever since that date in France and the Continent generally, and is still constructed by many engineers in this country, and is known as "Woolf's Engine," and employed for stationary purposes only. Both the cylinders are placed together at one end of the walking beam, the condensing cylinder being at the outer end, and the high-pressure cylinder close up to it with a proportionately less stroke. This arrangement is perfectly capable of carrying out the principle equal to any other. But the great pressure it exerts on the main centre of the walking beam, owing to all the power requiring to pass from the one end of the beam to the other, has caused it to be less extensively used than otherwise might have been the case; but more especially since 1845, when a patent was taken out by Wm. McNaught, wherein this great pressure is removed from the main centre by having the condensing cylinder only at the outer end of beam, and the high-pressure cylinder between the main centre and the crank, thus having the power equal on both sides of the main centre, and the pressure consequently merely nominal at that part. This arrangement is by far the best when the engine has to be of the walking-beam class.

Another good arrangement is carried out

in horizontal engines, with both cylinders lying side by side (generally cast together in one piece), and secured to a single sole plate; both piston rods are attached to one crosshead, so that one connecting rod conveys the whole power to the crank, nothing being in duplicate but the cylinders.

In the compound engine at present so largely employed in the British Navy, the cylinders, outwardly, are the same diameter, but the high-pressure cylinder, as previously mentioned, is generally made about $\frac{1}{3}$ less in area than the condensing cylinder. The space round the actual high-pressure cylinder being used to receive its exhaust steam until the valve of condensing cylinder opens to admit it, as the pistons do not move simultaneously, owing to the cranks being at right angles to each other.

It has been explained in the first part of this work that the nominal horse power of an engine is ascertained by assuming the mean pressure on the piston to be equal to 7 lbs. on the square inch, and the speed of piston equal to 220 ft. per minute. But as both the working pressure and speed of piston have been greatly increased since the above rule was first adopted, it fails to convey any adequate idea of the actual capabilities of the engine. Still, in all negotiations connected with the purchase of a steam engine, it is, as a rule, the nominal horse power alone that is referred to, although it is understood that with a pressure, say of about 60 lbs., and a piston speed of about 400 ft. per minute, fully six times the nominal power is got from a condensing engine.

As the term "Nominal Horse-Power" is only used when speaking of the steam engine as a marketable commodity, a particular size of cylinder may be called a certain nominal power by one maker, and a different nominal power by another, and unfair competition often takes place by two manufacturers offering for sale say an 80 horse-power condensing engine, one of whom means to give a cylinder 50 in. diameter, whilst the other calls a 40 in. cylinder the same nominal power. The rules now generally adopted in this country to determine the nominal power of the different kinds of steam engines are as follows:—

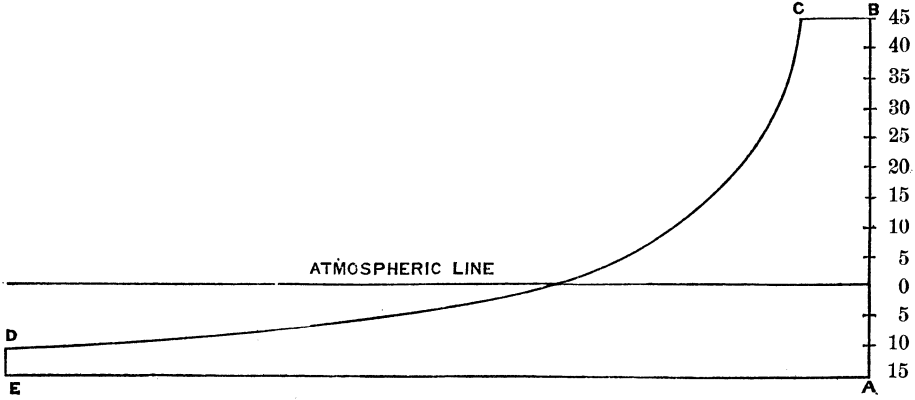
Rule to find the nominal horse-power of a high-pressure non-condensing steam engine: Square the diameter of cylinder in inches, and divide by 12, that is to say, a non-condensing engine with a cylinder=30 in. diameter, is called a 75 horse-power engine nominal, although it is capable of giving out at least three times the power when a pressure of say 60 lbs. is employed, and piston speed = 400 ft. per minute.

Rule to find the nominal horse-power of a single cylinder condensing engine: Square the diameter of cylinder in inches, and divide by 24, that is to say, that a condensing steam engine with a cylinder=30 in. diameter, is called a 37½ horse-power engine nominal, but is capable of working to at least six times its nominal power with 60 lbs. pressure and speed of piston=400 ft. per minute.

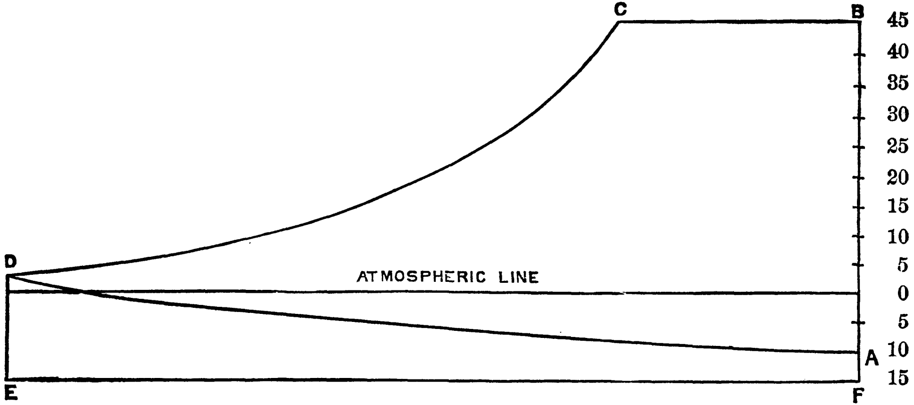
The rule now generally adopted by marine engineers for the nominal power of a compound engine is: Add the square of the diameter of each cylinder in inches together, and divide the sum by 30, that is with a compound engine whose condensing cylinder is 30 in. diameter, and high-pressure cylinder 17 in. diameter, is called a 40 horse-power compound engine nominal, and is also capable of working to at least six times that power with 60 lbs. pressure and speed of piston=400 ft. per minute.

Some diagrams are herewith given, the first two of which are theoretical, and the shape that would actually be got was there no loss of heat during the stroke from condensation or other causes. In the theoretical diagram, showing the expansion curve when the steam is expanded 12 times in a single cylinder condensing engine, A B represents the total initial pressure of 60 lbs., B C the constant supply of steam from the boiler at that pressure, C the point where the steam is entirely shut off$=\frac{1}{12}$th part of the stroke, C D the expansion curve formed by the decreasing pressure of the steam in the ratio that the space it occupies is increased by the advance of the piston, D E represents the terminal pressure, and E A the line of perfect vacuum. In the compound theoretical diagram, C D is the expansion curve formed from the high-pressure cylinder, and D A the expansion curve formed from the condensing cylinder, the line F B representing the initial pressure of 60 lbs., D E the terminal pressure in high-pressure cylinder, and initial pressure in low-pressure cylinder, and equal to 17.32 lbs., and F A the terminal pressure in low-pressure cylinder, and equal to 5 lbs.

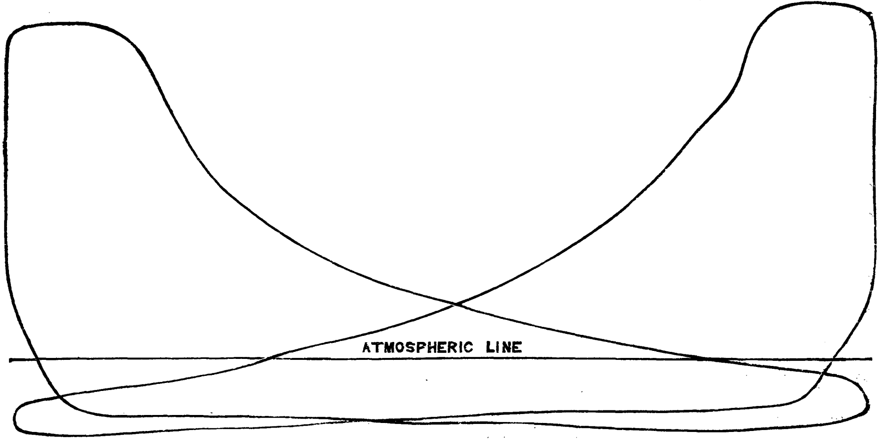
*A Theoretical Diagram showing the Expansion Curve in a Single Cylinder Condensing Engine, with Steam at 60 lbs. pressure above a perfect vacuum, expanded 12 times.*



*Theoretical Diagrams showing the Expansive Curve in both Cylinders of a Compound Engine, with Steam at 60 lbs. pressure above a perfect vacuum. Total number of expansions = 12.*

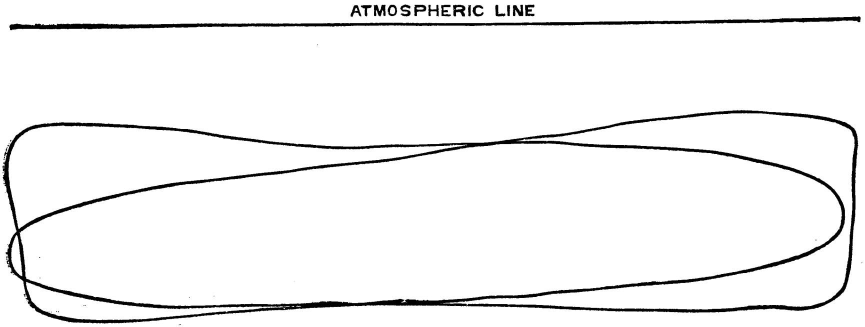


**HIGH PRESSURE.**—*Diagrams taken from a Compound Engine with Steam cut-off after the Piston has travelled one-eighth of the stroke in high-pressure Cylinder.*



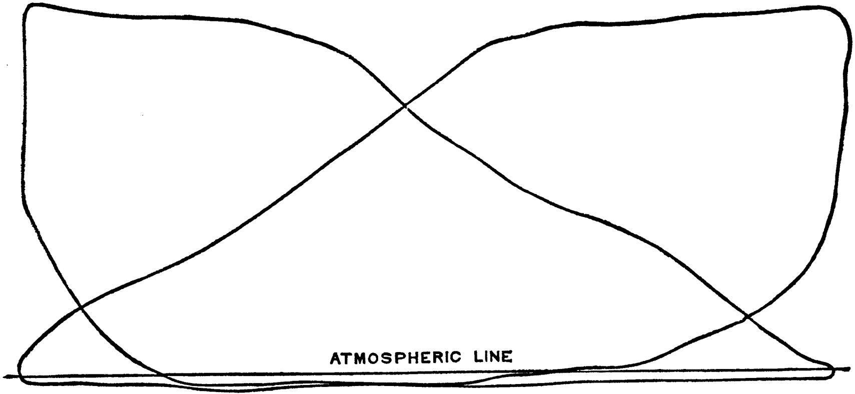
Scale—1-16 inch = 1 lb.

**Low Pressure.**—*Diagrams taken from a Compound Engine with Steam cut-off after the Piston has travelled one-eighth of the stroke in high-pressure Cylinder.*



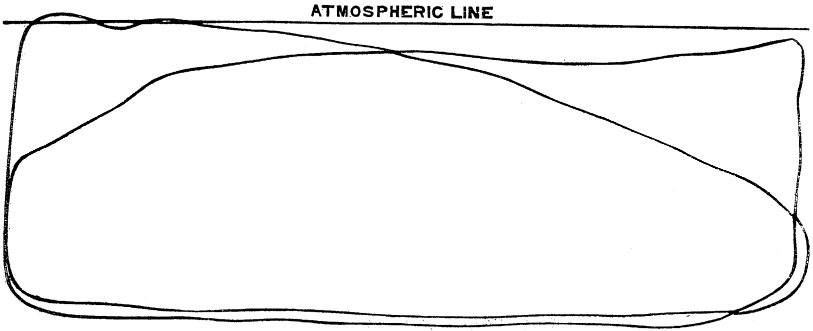
Scale – 1-8th inch = 1 lb.

**High Pressure.**—*Diagrams from the Compound Engine of the S. S. "Dunluce Castle"—Steam cut-off at one-half the stroke in high-pressure Cylinder.*



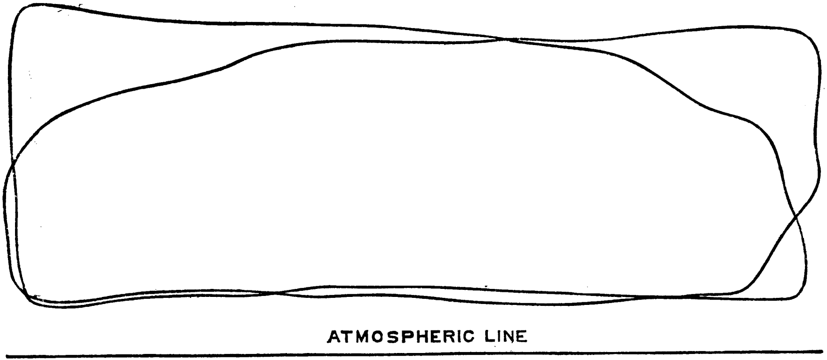
Scale—1-24th inch = 1 lb.

**Low Pressure**—*Diagrams from the Compound Engine of the S. S. "Dunluce Castle"— Steam cut-off at one-half the stroke in high-pressure Cylinder.*



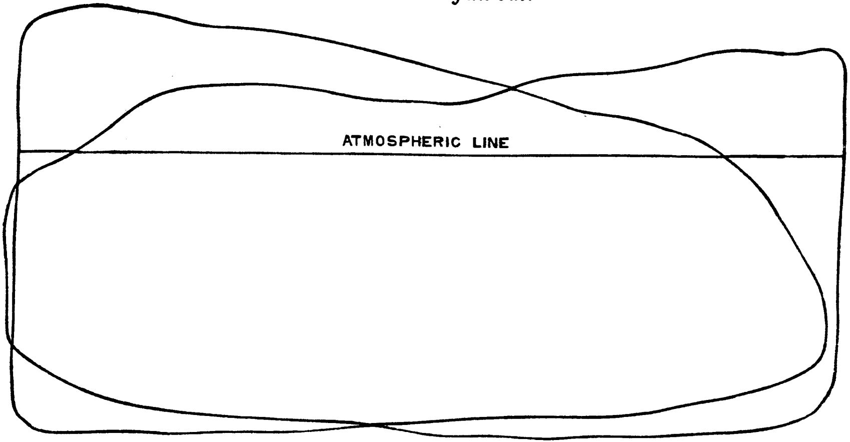
Scale—1-8th inch = 1 lb.

High Pressure.—*Diagrams from the Compound Engine of the S. S. " Dunluce Castle, with the Link full out.*



Scale—1-24th inch = 1 lb.

**Low Pressure.**—*Diagrams from the Compound Engine of the S. S. "Dunluce Castle," with the Link full out.*



Scale—1-8th inch = 1 lb.

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